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Fracture mechanisms under monotonic and non-monotonic low Lode angle loading

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ABSTRACT

Ductility of high-strength low-alloy steel S420MC was investigated by means of experiments and finite element analyses. Monotonic and non-monotonic low Lode angle experiments were carried out using double curvature specimens and punching tests. Punching tests allow investigating material behavior under zero Lode angle and from low to high stress triaxiality ratios. Investigated material exhibits significant increase of ductility with stress triaxiality decrease. Under low enough stress triaxiality, loss of load carrying capacity and fracture were not observed. Even if fracture is not observed under these conditions, pre-strains under very low stress triaxiality induce relative loss of ductility when the material is loaded again at higher stress triaxiality.

1. Introduction

Ductile fracture is the appearance of macroscopic cracks after significant inelastic deformation of a material. Predicting ductile fracture is of prime interest in mechanical engineering since failed components, generally, cannot ensure their in use functionalities. Fracture can occur at different stages of products cycle life. For metallic components obtained by forming process such as cold forging or stamping, fracture can occur during manufacturing or during use. Early works on fracture highlighted the significance of the stress state characterized by the stress triaxiality ratio and the Lode angle on the material ductility quantified by the equivalent plastic strain at fracture. Stress triaxiality ratio, Lode angle and equivalent plastic strain are defined respectively by Eqs. (5), (7), and (9) in Section 2.3. All along the paper, stress triaxiality will refer to stress triaxiality ratio. From a micromechanical point of view, ductile fracture is caused by void nucleation, growth and coalescence at high stress triaxiality and by shear bands at low stress triaxiality. These changes in the material microstructure induce at macroscopic scale a decrease of stiffness followed by fracture.

First investigations at microscopic scale were led by Mc Clintock [1], Rice and Tracey [2] who modeled the growth of cylindrical or spherical holes in a plastic matrix. These works showed the significance of the stress triaxiality on damage growth. Gurson [3] analyzed plastic cell containing a spherical hole and proposed a porous plasticity model that accounts for voids growth and for evolution of yield stress due to porosity. Based on the work of Gurson, Tvergaard and co-workers [4] proposed the Gurson–Tvergaard–Needleman (GTN) damage model that accounts for voids nucleation, growth and coalescence.

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Nomenclature

Stress and strain states characterization

p hydrostatic pressure
$\dot{\varepsilon}_{kl}$ plastic strain rate tensor
$\dot{\varepsilon}_{pl}$ rate of the equivalent plastic strain
η stress triaxiality ratio
θ_L Lode angle
σ_I first principal stress
σ_{II} second principal stress
σ_{III} third principal stress
σ_{eq} von Mises equivalent stress
σ_{kl} Cauchy stress tensor.

Material mechanical behavior

K material parameter of the power hardening law
n material parameter of the power hardening law
ε_0 material parameter of the power hardening law
σ_0 yield stress.

Mechanical test parameters: Tests on double curvature specimen:

d_1 thickness of the reduced section area of the double curvature specimen
e_1 thickness of the double curvature specimen
R_1 radius of the double curvature specimen
α_1 angle made by the horizontal axis and the direction of the resulting displacement or load for tests on double curvature specimen.

Punching tests

d_{BH} inner diameter of the blank holder
D_{BH} outer diameter of the blank holder
d_d inner diameter of the die
D_d outer diameter of the die
d_g internal diameter of the groove of the hat shape specimen
D_g external diameter of the groove of the hat shape specimen
d_h diameter of the blind hole of the hat shape specimen
d_p Punch diameter
e_2 sheet sample thickness
F_{BH} blank holder load
h height of the formed cylinder of the pre-strained specimen
j_1 clearance between the punch and the die
j_2 clearance between the upper and the lower part of the hat shape specimen
p_g groove depth of the hat shape specimen
p_h blind hole depth of the hat shape specimen
r_d edge radius of the die
r_e edge radius of the hat shape specimen
r_p edge radius of the punch.

Plan strain tensile tests

b_4 width of the plane strain tensile specimen
d_4 thickness of the reduced section area of the plane strain tensile specimen
l_4 height of the plane strain tensile specimen
r_4 shoulder radius of the plane strain tensile specimen
R_4 groove radius of the plane stain tensile specimen.

In another way, fracture was investigated at the macroscopic scale. Experimental data analyzed by Johnson and Cook [5] provided evidence of the influence of stress triaxiality on ductility. These authors proposed a fracture criterion where the equivalent plastic strain at fracture is modeled by a linear function of the exponential of the stress triaxiality.

More recent investigations showed that damage models and fracture criteria based on stress triaxiality only as a description of the stress state were unable to predict fracture for a wide range of loading conditions. Hambli [6] simulated the